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Psychophysical estimation of the effective level of internal noise in the auditory system

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PSYCHOPHYSICAL ESTIMATION OF THE EFFECTIVE LEVEL OF INTERNAL NOISE IN THE AUDITORY SYSTEM

by

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PSYCHOPHYSICAL ESTIMATION OF THE EFFECTIVE LEVEL

OF INTERNAL NOISE IN THE AUDITORY SYSTEM

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Table of Contents

Table of Contents (Cont'd.)

List of Tables

List of Figures

Some versions of the theory of signal detection (TSD) assume that the observer in a detection task is an energy-dependent system (Jeffress, 1964). The theory treats detection as dependent upon the separation between a noise and a signal-plus-noise distribution. Until recently it was thought that the detection concepts might only apply in situations where an external masker is present (Levitt, 1969). Watson, Franks, and Hood (1967) showed that the theory also provides a good description of detection performance in the quiet; i.e., with no external masker. Therefore, an internal noise was proposed as the factor limiting detection in the absence of external masking. As a first approximation, this internal noise was assumed to be one critical ratio below the signal level required for detection in the quiet, just as a noise is one critical ratio below a signal just masked by that noise in a high-level masking condition.

The purpose of the experiments reported here was to devise a psychophysical method for further tests of the internal noise hypothesis. The final statistic desired was the effective spectrum level of the noise of the human auditory system, when that system is excited by a standard laboratory earphone. An auxilliary purpose was to gain some further information on the slope of the psychometric function for the detection of tonal signals as a function of signal frequency and of the level of the masking noise.

Review of the Literature

Masking

Masking is the process of imbedding a signal in such an amount of non-signal related energy that detection of that signal is degraded. Tanner (1958) discussed three types of masking. Signal masking is the most common type. It is the type of masking found when white noise is presented into the same auditory field as a signal to be detected, the result being that the detection performance is degraded. Until recently signal masking was the only type discussed. Another type of masking is distortion; any process which acts to change the signal so that its presence becomes unsure for the observer because the modified parameters of the distorted signal do not match those for which the observer is looking. Consequently the observer must alter his mode of detection so that a larger set of parameters may be considered, resulting in a degrading of detection. A third type of masking is that of distraction. It is any process which acts to impede the observer's detection by demanding that he perform some other task simultaneously; as, listening to two signals or keeping track of past responses.

The type of masking with which this paper is concerned is signal masking by band-limited white noise. The concepts of distortion and distraction, while probably present in any detection task, are not considered.

A concept which is important in signal masking is that of the critical ratio. The critical ratio (CR) is the difference between the spectrum level of the noise masker and the level of a just-detectable signal in that noise. Hawkins and Stevens (1950) found that the CR is constant over a wide dynamic range of noise. Only when the noise begins to approach the level which is close to the threshold of the signal to be detected does the CR change; it becomes larger. The concept of internal noise, rather than a lower limit of sensitivity (threshold), could account for the increase in the CR at low noise levels. That is, the apparent increase in the CR at low masking levels might be due to the presence of an additional, constant component of the noise; i.e., "the internal noise."

Another important concept in signal masking is that of the critical band. The critical band (CB), operationally, is that band of noise which is effective in masking a signal, which if increased in width does not increase the masking effect, and which if decreased in width decreases the masking effect. Fletcher (1940) assumed in his model of the CB that it was equal to the antilog of the CR. Thus

$$10 \cdot \log CB(Hz) = CR(dB).$$

While the CR and the CB are correlated functions of signal frequency, the CB is 3-4dB greater than the CR. (Hawkins and Stevens, 1950)

The conventional method for estimating the width of the CB has been the band-narrowing experiment (Fletcher, 1940). Bourbon, Evans, and Deatherage (1968) conducted a modification of this experiment. They used signal frequencies from 250 to 400Hz in octave steps. They determined the ratio of signal energy to noise power per unit bandwidth (E/No) at which the subject has a probability of correct response of 0.54 in a two alternative, temporal forced choice (2ATFC) task involving the detection of a signal in a wide band of noise. They then reduced the band-width by raising the cutoff frequency of a high-pass filter with a 98dB per octave slope, until the lower limit of the CB was defined as the point at which the percent correct [p(c)] reached half of its maximum value. The process was repeated with a low-pass filter. The distance between the lower and upper limits established the CB. Their results deviate from Fletcher's in two ways. As No was decreased, the width of the CB increased at all frequencies except 4000Hz. Also, all of their CB's were larger than one-tenth the antilog of the CR for the same signal frequency.

Zwicker, Flottorp, and Stevens (1957) studied the CB for loudness summation. They defined the CB around a center frequency as the Δf (difference between the highest and lowest frequency) above which the loudness of a composite tone begins to grow and below which there is no loudness change. Using this method they have found the widest CB's yet reported. The critical band width seems to be very much a function of experimental method as well as of stimulus parameters.

Watson, Franks, and Hood (1967) found the CR's for six signal frequencies using wide band noise, in order to estimate the effective spectrum level of the internal noise. The purpose of the present experiments was to replicate the estimation of the effective spectrum level of the internal noise as done by Watson, Franks, and Hood, using band-limited rather than wide-band noise. Since the goal was to have a band of noise not exceedingly wide and yet not so narrow as to reduce the masking effect, band-widths about 20 percent wider than those reported by Zwicker, et al., were used.

Since the masker considered in this paper is a noise, some comments about types of noises are in order. There are many types of noises ranging from the Gaussian white noise used in most psychophysical experiments to many other random fluctuations in the level and frequency of events. Green (1960) placed some constraints upon theorizing about internal noise in that there is more than a single type of noise. He listed three mandatory steps in building a theory about internal noise if the theory is to be of any use to other experimenters. The characteristics of the noise must be specifically stated; that is, its statistical definition is essential. The way in which the noise interacts with the detection process or the discrimination process must also be clearly stated; the way in which the noise interacts with other noises, additive or multiplicative, must be considered. There must be specific evaluation of the effect of the noise upon the performance of the observer. Keeping this in mind and adding a definition of the system of concern as beginning at the earphone diaphram and ending at the final response stage (such as the fingertip for a 2ATFC task or the scalp for an evoked auditory response experiment), a review of the literature concerning different types of noise is essential.

From the literature, there appear to be roughly five types of noise which have been studied. They have been the acoustic noise in the ear canal, the system neural noise, undefined constant-level background noise, noise due to criterion or memory wobble, and detection inefficiency resulting from lack of information about that which is to be detected, which has also been interpreted as a class of noise.

Acoustic Noise

Harris (1968) gives the most recent treatment of the subject of Brownian motion and its relation to the threshold of hearing. For the Brownian motion of air he found the band level of that energy between 2500 and 3500Hz to be 18dB below the threshold at 3000Hz. The spectrum level would be 48dB below that threshold or at a level of about -36dB SPL. This level could act very little as a masker of tones and its relative contribution to any other noise would be small. Even though the Brownian motion does have the characteristics of other noise, its low level could have little if any effect on setting the lower limit of sensitivity.

Shaw and Piercy (1962) were interested in the relation between the physiological noise under the earphone cushion and audiometric measurements. They measured the level of the noise under the cushion by means of a probe tube for the frequencies below 500Hz. They used three types of cushions; the MX41/AR with an enclosed volume of 13 cc., a circumaural cushion with an enclosed volume of 30cc., and a circumaural cushion with an enclosed volume of 150cc. They made measurements in third octave bands. The band levels as a function of frequency and enclosed volume are shown in Table 1.

Table 1 shows that the noise levels have an inverse relation

Table 1. Band Levels of Noise in the Ear Canal As Measured by Shaw and Piercy (1962).

	Size of Enclosure.		
Center Freq.	13cc	30cc	150cc
16.0Hz	--dB*	--dB	72dB
31.5	77	77	62
63.0	57	57	38
125.0	40	40	23
250.0	20	15	4
500.0	-3	-3	--
1000.0	-10	-10	--

Table 2. Comparison of Freefield Physiological Noise Measurements with those under the MX41/AR Earphone Cushion (Shaw and Piercy, 1962 & 1963).

Center Freq.	FFPN	MX41/AR	Diff.
40Hz	40dB*	77dB	37dB
63	15	57	42
125	10	40	30
250	-10	20	30
500	-10	-3	7

*All noise levels are in dB band level.

to enclosed volume and frequency. Shaw and Piercy attribute some of the noise to blood and muscle movement. The shift to higher levels for lower frequencies is probably related to the low frequency of body movements. The decrease in level with increase in enclosed volume may be related to the fact that as the volume increases so does the area of the surrounding surface, resulting in a decrease in the force per unit area. As a result of their data, Shaw and Piercy concluded that the thresholds at 125 and 250Hz obtained with the standard MX41/AR earphone cushion are elevated by the masking effect of the physiologic noise under that cushion due to the small volume of air enclosed.

Piercy and Shaw (1963), using a loudness balance technique, estimated the level of the free-field physiologic noise (FFPN). Those estimated levels are shown in Table 2. Entered in the table are also the levels under the MX41/AR cushion as a function of frequency and the difference between those levels and the levels for the FFPN condition. At both 125 and 250Hz the free-field condition is 30dB quieter than under the standard cushion. It is thus again suggested that the thresholds at those frequencies are elevated by the degree that they are masked by the increased noise level under the standard cushion. The noise at low frequencies in the ear canal is very real, with the major component being the physiologic noise and a <u>very</u> minor component being noise from Brownian motion of the air in the ear canal.

Neural Noise

If spontaneous neural activity is considered to be neural "noise," then the observations of Kiang (1965) are of interest. He discussed two points. Most units with a high rate of spontaneous activity also have a high maximum rate of steady discharge under continuous stimulation. Those units with a high spontaneous activity rate (greater than 15 spikes per second) are more sensitive than those with a lower rate of spontaneous activity (less than 15 spikes per second), but there is no frequency effect. Kiang (1967) also found that the lower the characteristic frequency of a unit, the less sensitive it is.

Combining those observations, a theory can be proposed about the effective level of neural noise. Assume that all units have a uniform spontaneous activity level of greater than 15 spikes per second which infers that all of the units are equally sensitive. Assume also that due to the physiologic noise found by Shaw and Piercy (1962) that those units with a lower characteristic frequency have been inhibited and consequently their spontaneous rate appears to be lower. It would then appear that those units with a high spontaneous activity are the most sensitive units in the system, when in fact they may all be equally sensitive; the psychoacoustic measure of sensitivity following the same general shape of the tuning curve of Kiang due to the masking properties of the noise. What is being proposed is two overlapping distributions of noise, the acoustic one falling with frequency and the neural one being of a constant level. The physiologic noise would act to set the lower limit of sensitivity at frequencies below 1000Hz and the neural noise would set the lower limit of sensitivity at frequencies above 1000Hz. This is essentially an extension of the hypothesis proposed by Watson, Franks, and Hood (1967).

There are other types of noise such as background noise, noise due to criterion or memory wobble, and noise from system processing inefficiency to be considered but they have not been measured in any objective manner. They can be estimated in their effective masking level, but these estimates are confounded by the involvement of many different types of noise. Some have been specified by descriptive statistics such as the mean, sigma, type of distribution, and randomness and some have not been specified at all. In any case, they are assumed to be internal and assumed to interfere with detection.

Constant Level Background Noise

Pfafflin and Mathews (1962) proposed an energy detection model for monaural detection. They tested the model with a pedestal experiment. At first they assumed a noiseless model, but in order to make the model fit the data thay had to assume an internal noise. For their model a noise of an additive nature, that was independent of the signal level but whose effect was dependent upon the level of the external masker, accounted for the data. Their noise was assumed to be random with a normal distribution.

Diercks and Jeffress (1962) studied the interaural phase of the signal and the absolute threshold, for a pure tone of 250Hz. They used the interaural conditions of S_m (signal monaural), S_o

(signal in phase), and S_π (signal out of phase by 180°). They found thresholds of 30.3dB, 27.5dB, and 26.6dB SPL respectively. They concluded that the differences between these thresholds were interaural phase effects much like those seen in the masking-level-difference phenomenon at high levels of external masking noise. They hypothesized the existence of an internal noise with a low, positive interaural correlation that could mix with the external noise in an additive manner, thus changing the correlation of the total noise. They concluded that the "absolute" threshold at 250Hz seemed to be a masked threshold, with internal noise doing the masking.

Robinson and Jeffress (1963) developed an interaural noise correlation formula. The formula is:

$$r = e_c^2/(e_c^2 + e_u^2),$$

where e_c is the rms voltage of the correlated noise and e_u is the rms voltage of the uncorrelated noise. They used three noise generators for this experiment; one providing a signal correlated 1.0 to both ears, the other two going to a different ear. The voltages were read and the correlation computed. As the correlation changed from 1.0 to -1.0 the masking level difference (MLD) shifted by 14dB for both the S_o and S_π conditions.

Dolan and Robinson (1967) expanded the experiment to try to estimate the correlation of the internal noise by introducing external noise at very low spectrum levels. They assumed the internal noise to be additive to the external noise. Their formula for the correlation was:

$$r^2 = (a^2 + e_c^2)/(a^2 + e_c^2 + e_i^2),$$

where a is the amplitude of the signal, e_c is the power of the correlated noise introduced by the experimenter, and e_i is the power of the internal noise. The MLD found at a low level was compared to the MLD for high masking levels to see what the interaural correlation would have been. Since r, a, and e_c were known, the equation could be solved for e_i. For the present purposes, the important concept is that the effect of the internal noise upon detection is entirely dependent upon the level of the external masking noise.

Noise Due to Criterion Instability

Eijkman and Vendrik (1966) discussed the specification of a system by its internal noise. They hypothesized three classes of internal noise. The first class was a noise peculiar to each input channel such as a noise of audition, vision, and olfaction. A second class of noise was assumed to be temporal wobble or variance common to all input channels. Finally, they assumed a criterion instability common to all channels.

There are two ways in which noises can be combined, by addition and by multiplication. The authors considered all three classes of noise described above to be multiplicative. A noise considered to be constant level background noise is additive. Given an external noise (No_e) and an internal noise (No_i), the total noise (No_t) would be

$$No_t = No_e + No_i$$

for the power functions, and the total noise in decibels is given by

$$No_{tdB} = 10 \cdot \log[10^{(No_{edB}/10)} + 10^{(No_{idB}/10)}].$$

For multiplicative noise the corresponding formula is

$$No_t = No_e \times No_i$$

for power, and expressed in decibels the total noise is

$$No_{tdB} = No_{edB} + No_{idB}.$$

For an additive noise the amount of change in decibels in the total noise is primarily dependent upon the level of the highest noise component in the total noise, so that for an external noise 20dB greater than the internal noise the total noise would be essentially equal to the external noise. For multiplicative noise the total always depends heavily upon the size of both components. The incorporation of a noise of 5dB would result in the total noise increasing by 5dB regardless of the size of the other component. Thus while the size of the internal-to-external noise ratio for the additive case depends upon the size of the largest component, for the multiplicative case the ratio depends upon the difference between the two noises in decibels and the ratio would be equal to that difference.

Thijssen and Vendrik (1968) discuss the multiplicative noise model in terms of two sub-models. They proposed a simple multiplicative noise and also a multi-range meter model such that the noise is additive within a range, but multiplicative across ranges. In either case the effect is to degrade detection. For the multi-range meter model there would be an optimum S/No within a range. For the simple model detection would be independent of the range and would thus be constant for a given value of S/No.

If either model is to describe the detection of a signal in noise, the multi-range meter model has the greatest potential for it allows for some shift in the size of the external-to-internal-noise ratio.

Swets, Shipley, McKey, and Green (1959) used a multiple observation technique and found that the detectibility index, d', increases with the number of observations which the observer makes of a constant input. They then computed the ratio of internal to external noise by assuming that the multiple observations allowed an averaging process which reduced some of the masking effects of the internal noise. The formula for the constant was

$$K = d'_n/d'_1.$$

The constant was equal to 2.00 for variable external noise and 1.20 for constant noise. They expected that if the external noise level were increased that K should increase to about 200. However, K was found to be independent of the external noise level over a 70dB dynamic range. They therefore hypothesized an internal noise of a constant ratio to the external noise with K = 2.0.

Watson (1962) derived the ratio K in a similar manner in a multiple observer problem. By combining the data from three subjects for a rating scale he derived what he called the "group ROC" curve. He found a constant of 1.03 for $K = d'_g/d'_i$. Had he tried, it too would probably have remained constant over a wide range.

The four above papers treated a noise which does not have the same characteristics as would thermal noise. The noise fits the description of an internal noise in that it is a within-subject variance that does degrade detection as evidenced in a higher d' for the n observations than for a single one for Swets, et al., and by a higher group d' than individual d' for Watson. Since its effect is independent of the noise level it then seems to fit the Tanner (1959) definitions as a distracting noise rather than as a signal masker. As a source of variance in the data and as a limitation upon performance it must be considered. It is not, however, the kind of noise which concerns this thesis.

Inefficiency

The human observer has been viewed as less efficient than the ideal observer of TSD. Internal noise cannot completely explain this inefficiency if the noise is of any of the single types described above. The MLD does not describe a situation where the human is approaching ideal detection, for if the ideal were given interaural phase information it could achieve perfect detection for any interaural correlation other than 1.0. The only way for the human to approach ideal detection is to process information of no value to the ideal but of value to the human.

M. M. Taylor (1968) devised a method whereby the human observer is given information that is of no value to the ideal. The observer was given a monaural detection task. In the non-test ear he was given a cue of the same stimulus parameters other than intensity as the test signal. The cue was at a perfect detection level. The subject detected the signal in the test ear by noticing a change in the cue signal in the non-test ear. Taylor found that his observers were operating at better-than-ideal performance. The results were approaching d' $(2E/No)^{1/2}$. Information (the cue) which would be of no value to the ideal of TSD is apparently of great value to the human observer. It is unclear as to how to classify a noise to describe this data. Taylor may have demonstrated an inadequacy in the ideal detector model rather than theoretically impossible performance on the part of the human. The model is monaural; the Taylor experiments are binaural.

Conclusions

All of the above papers have viewed the detector as an energy dependent system. While some detection research suggests that there is no energy threshold the problem is to account in some other way for the lower limit of sensitivity. One way to account for the limit is to assume an internal noise, and there is evidence supporting the existence of such a noise. However, precise specification of this noise is difficult. As suggested above, the literature shows two distinctive types of noise; the additive noise and the multiplicative noise, the former mixing with any external noise and the latter being independent of external noise. This thesis is an attempt to estimate the effective masking level of the former type of noise.

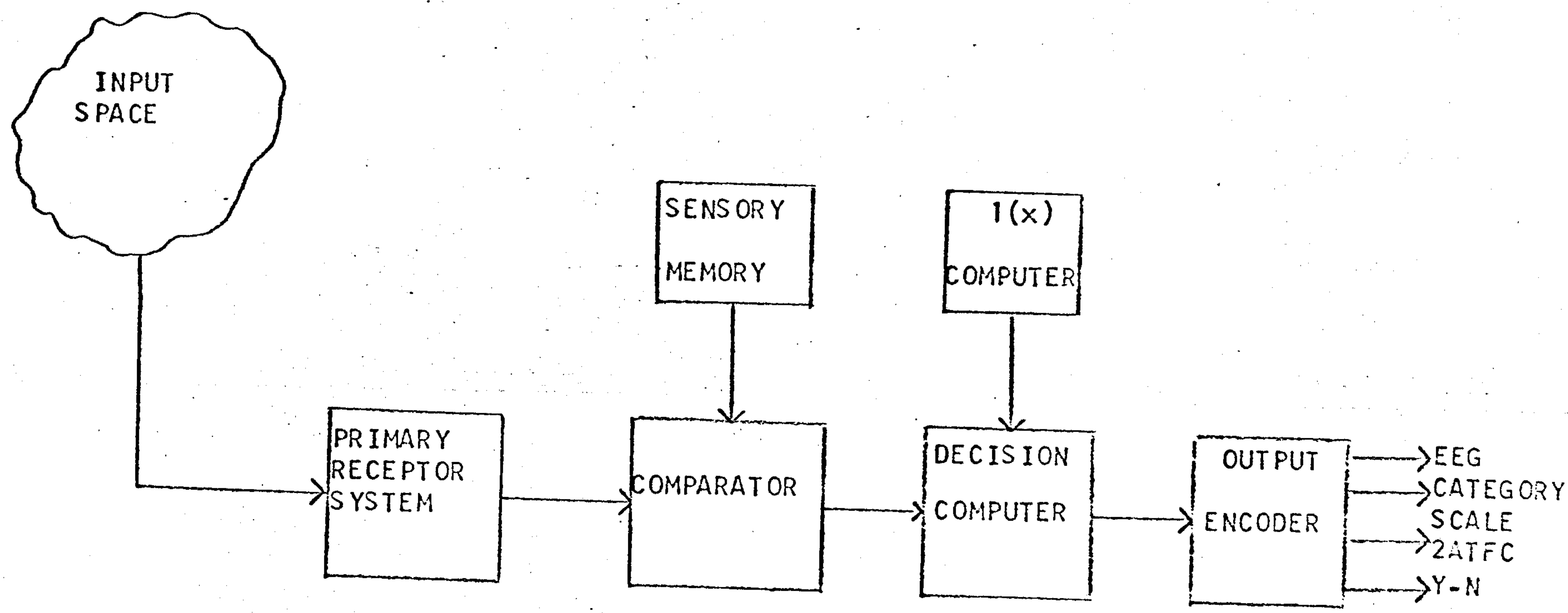

Fig. 1. Tanner's (1961) Model of the Energy Detector
(See text for explanation.)

Tanner's Model of the Energy Detector

Tanner (1961) published a block diagram of the ideal observer of TSD, as shown in Figure 1. The model assumes that the input space consists of all possible sensory inputs which can affect the observer. Presumably the input space is under experimenter control. At the primary receptor system portions of the input not essential to the task at hand may be filtered out while that information which is essential to the task is passed to the comparator. Obviously, the ear is the primary receptor for an auditory detection task.

The sensory memory contains a template of the signal to be detected. The observer is given information about the signal by the experimenter or he gleans it from experience at the task. Information would be of the type; 4000Hz at 40dB SPL, Sm, 150msec duration, 10msec rise-fall time, occurring during the green light. The observer constructs a template which carries that information, the template being stored in the sensory memory system.

The outputs of the primary receptor system and the sensory memory are inputs to the comparator system. At the comparator the input from the receptor is compared to the stored template and a deviation statistic is computed. That statistic can be viewed as a likelihood ratio, $l(x)$, that the signal is that which the template defines. The $l(x)$ computer computes the $l_c(x)$ required to make a decision that a signal was presented. This $l_c(x)$ can be viewed as the criterion which must be exceeded before the decision will be made that a signal was presented. The criterion is established on the basis of the costs and values of all possible stimulus-response combinations.

The <u>decision computer</u> compares the $l(x)$ from the comparator to the criterion from the $l_c(x)$ computer and issues a decision based upon whether the criterion was exceeded or not. The <u>output encoder</u> transforms the decision from the decision computer into some form of output. The output can be in many forms ranging from the cortical response to psychophysical responses, as yes-no responses, or ratings, or the 2ATFC judgments used in these experiments. The output encoder can be viewed as a filter of variable band-width. As the band-width decreases, the response becomes stimulus dependent, i.e., is less noisy. Along a continuum of noisiness of response from most to least noisy would be: the EEG response, the category-scale response, the rating-scale response, the 2ATFC response, and the yes-no response. As the response carries less information about the nature of the stimulus, the less noisy it is apt to be.

Rather than try to assign types of noise to each sub-system it is more appropriate to state that the noise in the input space and in the primary receptor system acts as a masker of the signal to be detected, while the noise in other systems (memory, criterion instability, etc.) produces inefficiency which is constant and independent of the stimulus parameters, or even of the sensory system under study.

It is worthwhile to keep the model in mind while thinking about internal noise. While there may not be simple physiologic correlates to the sub-systems within the model, it can show what kind of processes are being limited, possibly by noise. Methods for studying specific types of noise can be suggested by the model and the results of these studies may help to confirm the model or to reject it.

Statement of the Problem

The basic hypotheses of this thesis are derived in part from TSD. The ideal observer is assumed to depend on energy for his detection decisions. The human observer may be similarly energy dependent. Consequently, the lower limit of sensitivity may be set, not by a threshold, but by internal activity which acts as a masker of information-carrying energy. Thus the hypothesis is that there is an internal noise which prevents the observer's responses from appearing to be completely dependent upon externally introduced energy. The internal noise is assumed to act in the same manner as would an external additive masking noise.

An internal noise at a critical ratio below a just-detectable signal in the absence of external noise was assumed by Watson, Franks, and Hood (1967) to account for the similarity in their detection in the quiet data to data obtained from experiments using high masking levels. To test the hypothesis that the internal noise was at that level and had an essentially Gaussian distribution, they devised the following experiment.

The signal level required for $d'=1.0$ detection in the absence of external noise was determined at frequencies from 125 to 4000Hz in octave steps. Using the Hawkins and Stevens (1950) values of the CR, they estimated the level of internal noise for each of those frequencies. They assumed internal noise to be additive to the external noise. If at 125Hz the internal noise was assumed to have an effective masking level of 29dB SPL, then the addition of an external noise of the same level would result in an overall effective masking level of 32dB SPL. Thus a 3dB masking effect would be expected. They found a 2.7-to-3.5dB of masking.

The purpose of these experiments was to replicate the study by Watson, Franks, and Hood (1967), using narrow bands of noise. They are a retest of their hypothesis done intensively at 125, 1000, and 4000Hz. Band-limited noise was used in order to avoid the spread of energy into non-test frequency regions. The sensitivity curve is changing so rapidly between 125 and 250Hz that a band of noise at 30dB SPL low passed at 300Hz would just be barely audible while a wide band of noise would be extremely audible. The use of wide band noise may act to confound the detection task for the audible noise is not in the region of the signal to be detected. The bands of noise centered around 1000Hz and 4000Hz were inaudible.

Method

Subjects

The subjects who participated in this experiment were four young adults with clinically normal hearing (ISO, 1964) as determined by a Bekesy sweep-frequency audiogram. Two were male, two were female.

Apparatus

The apparatus was the General Auditory Discrimination Apparatus (GADA) of the CID Signal Detection Laboratory. GADA consists of signal and noise generating apparatus, gating apparatus, attenuators, timing and control apparatus, and response recording apparatus. GADA was modified for these experiments so that a signal generated by an oscillator (Hewlett-Packard 200CU) was split by a resistive network into two 600-ohm sources. One source was reduced in amplitude by 2dB and fed into one side of a relay-controlled signal selector. The other source was fed, unattenuated, into the other side of the selector. The selector determined which signal level was to be presented, as regulated by a punched-tape reader. The output of the selector was fed into an electronic switch (Grayson-Stadler 829C) which gated the signal upon a pulse from the timing apparatus. The output of the switch was introduced, via an attenuator, into an amplifier (Dynaco Mark III-500). The signal out of the amplifier was attenuated 20dB and, via a 4-way resistive splitter, fed into a bank of four attenuators, thus giving separate control of signal level for each of four earphones.

In a separate room from the control room were four sound isolation chambers (Industrial Acoustic Company, Model 401A). The line from each of the four attenuators went into one of the chambers and into a mixing network which mixed signal with noise. After the mixer the line impedance was changed from 600 ohms to 10 ohms by a matching transformer. The output of the transformer drove the earphones (Telephonics, TDH-49). The noise circuit was similar, with a noise generator (Grayson-Stadler, Model 455C) as the source and an additional amplifier (Western Electric, Model 124E).

In GADA, an ICONIX timing system providing 10 variable-duration intervals is used to control the durations of all events. The contacts of ten four-pole-double-throw relays, each corresponding to a given ICONIX interval are available for switching at a patch board receptacle (MAC, Model 901). The use of the relays allows the programming of any event in any time interval by wiring for that event on the MAC panel. Also interfaced to the MAC panel is a count-down counter and a punched-paper tape reader. The four subjects' response boxes and a set of four counters for each subject are all displayed on the panel terminals as well.

For the first two experiments the signal was presented at two levels with 2dB separation. Since the experimental method was 2ATFC, the *a priori* proabability of any one level occurring in one of the intervals was 0.25. The subject did not have to identify the signal level which he heard; his task was only to indicate during which interval the signal occurred. For the third experiment, the signal was a constant level and the *noise* was presented at two levels within a block, using the signal-select relay.

Noise was presented in only the first and third experiments. The noise was band-passed filtered with a pass-band centered at either

125, 1000, or 4000Hz. The pass-bands were about 20% wider than the critical band estimates by Zwicker, et al. (1957). The cut-off frequencies and the bandwidths are listed in Table 3 by center frequency. The cut-off frequencies are figured at half-power points. Figure 2 is the block diagram of the acoustics.

The second experiment was run in the absence of external noise. The noise spectrum levels in the first experiment were 50dB SPL at 125 and 1000Hz, 40dB SPL at 4000Hz. The noise spectrum levels in the third experiment were presented relative to the estimated internal noise at 3dB above it, at it, 3dB below it, or no noise was presented at all. The average level of noise in the third experiment was 30dB SPL at 125Hz, -15dB SPL at 1000 and 4000Hz.

Due to the low signal levels and noise levels in the last two experiments, it became mandatory to measure the noise in the audiometric booths. Table 4 shows the octave band levels in the booths as measured by a Breul and Kjer Model 2203 sound level meter with a Model 1613 filter plug-in. They are converted to spectrum levels. The spectrum levels under the MX41/AR cushions are calculated using the attenuation characteristics of that cushion given by Hirsh (1952). Those spectrum levels of the noise under the cushion are well below the levels of the weakest noise used in these experiments. The measurements were made with all motors and air circulation systems off in both the booths and in the control room.

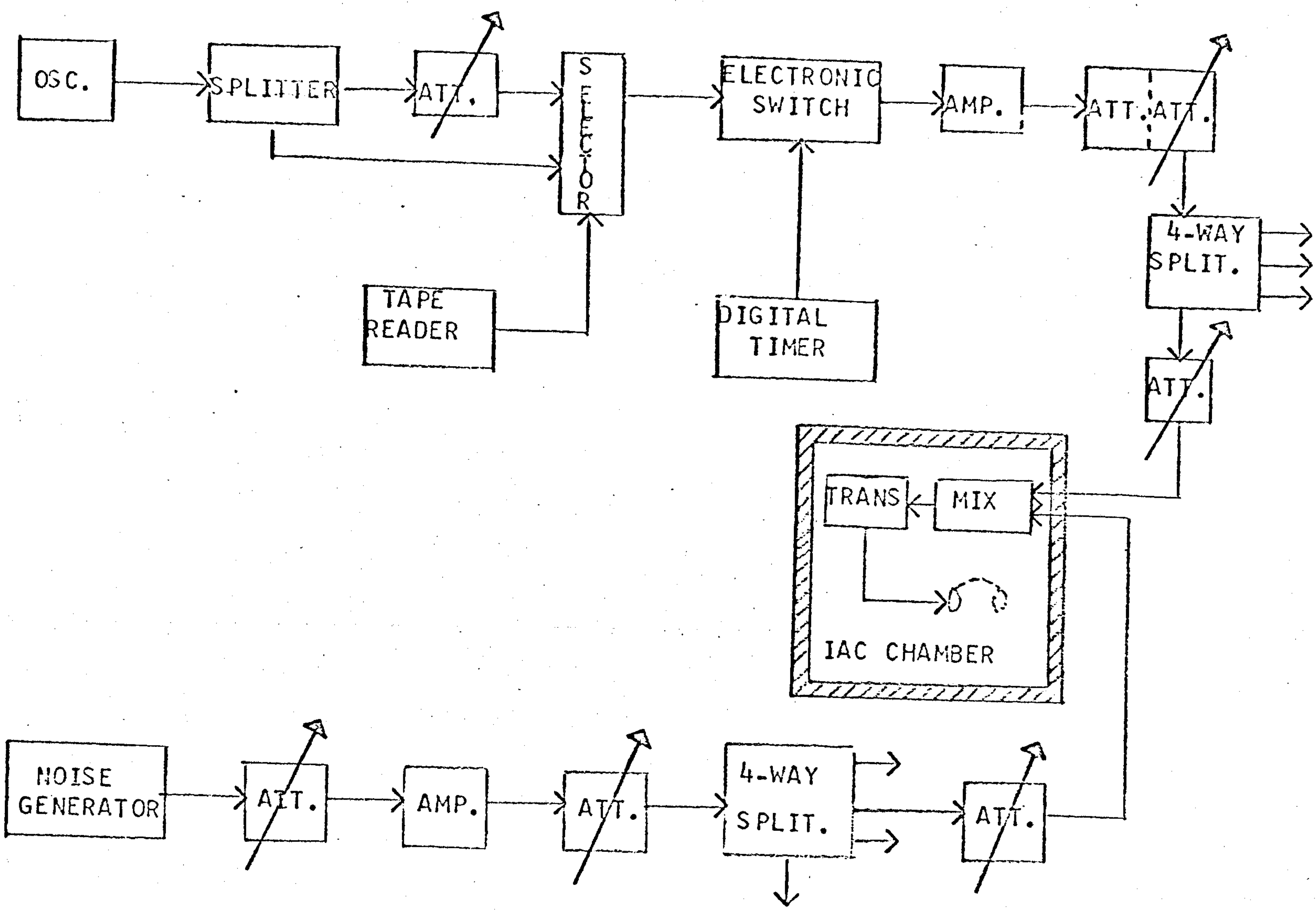

Fig. 2. Block Diagram of Auditory Apparatus of GADA.

Table 3. Filter Characteristics of Band-Limited Noise.

Center Freq.	Low Cutoff*	High Cutoff	Band Width
125Hz	0Hz	240Hz	240Hz
1000	720	1320	600
4000	2880	5280	2400

*The cutoff frequencies were determined at the half-power points.

Table 4. Noise Levels by Frequency in the Subjects' Booths and under the MX41/AR Earphone Cushion.

	In Booth		Under Cushion
Center Freq.	Band Level	Spectrum Level	Spectrum Level
125Hz	29dB	9dB	-1dB
250	13	-11	-19
500	7	-20	-27
1000	7	-23	-39
2000	8	-25	-55
4000	10	-26	-61

Procedure

The trial sequencing for all three experiments was the same. The temporal cuing information was given to the subjects by means of lights on their response boxes. Each trial began with a 150-msec flash of a yellow warning light. A red light on the left of the box flashed for 150msec, 500 msec after the warning light, cuing the first observation interval. A second red light, on the right, flashed for 150 msec, 500 msec after the termination of the left light, to cue the second observation interval. The response interval began at the termination of the second light and lasted one second. During that time the subject had to press a button below each of the interval lights to inform the experimenter during which interval he thought the signal had occurred. If he responded in time, a light was turnéd on under the button which he had pressed, and remained on until the end of the response interval. The duration between the end of the response interval and the onset of the next warning light was 450 msec. The trial sequence is shown in Figure 3.

The subject listened to 100 trials during a five-minute block. Seven blocks of 100 trials were run during each one-hour listening session for 35 minutes of actual listening time, the other 25 minutes allowed one five-minute break and five three-minute breaks between blocks. At the end of each block the subject was told his percent of correct detections for that block. In each experiment, three sessions of practice at 500Hz preceded six experimental sessions. One experimental session was run per day.

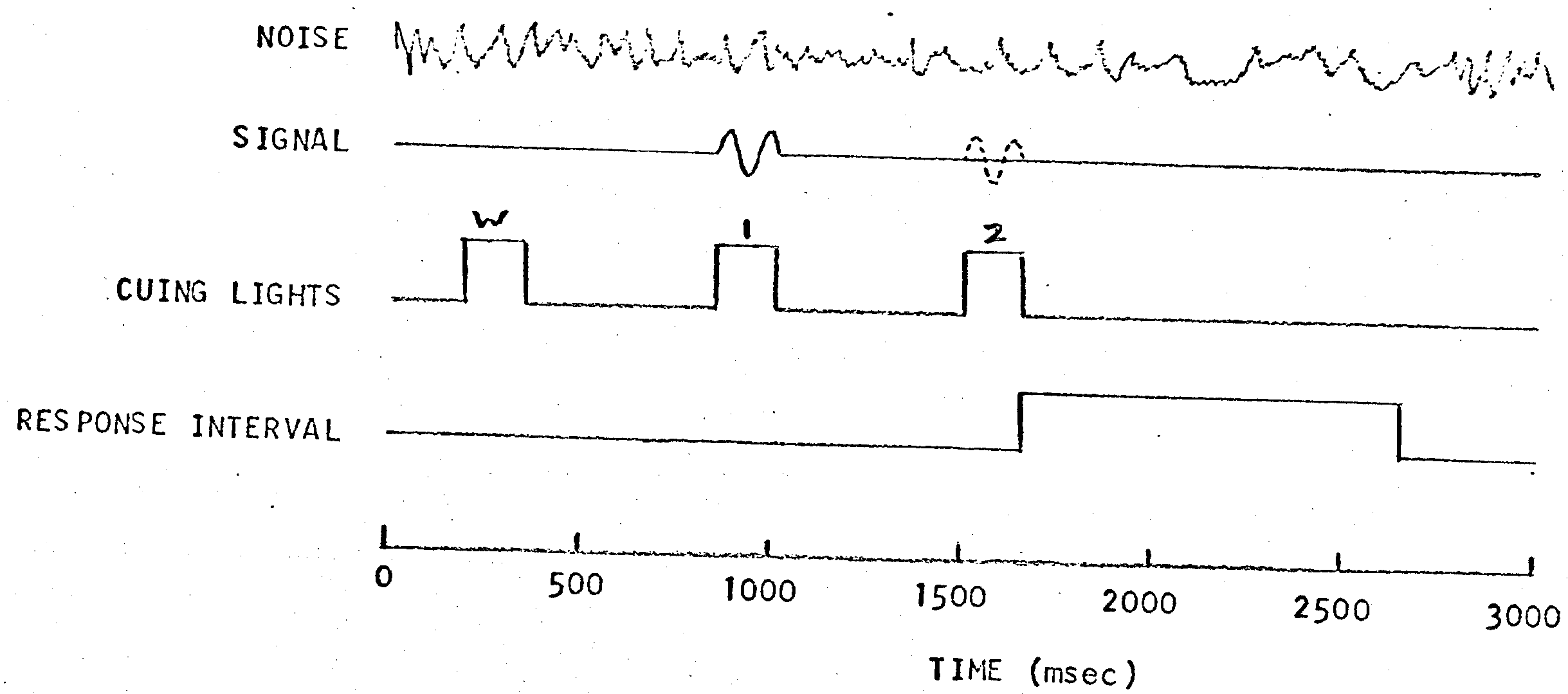

Fig. 3. Temporal Trial Sequence. The noise is continously on, the signal may occur during either Light 1 or 2. The Response Interval lasts for 1.0 sec and begins at the offset of the second Interval Light.

The data were collected by counters forming a two-by-two matrix for each subject. The matrix configuration is shown in Table 5. The percent of correct judgments was calculated after

Table 5. Response Recording Matrix

	n correct	n incorrect
High	$f(C\|H)$	$f(I\|H)$
Low	$f(C\|L)$	$f(I\|L)$

$$p(C) = \frac{f(C|H) + f(C|L)}{N}$$

each block for each signal level.

Prior to the experiment, each earphone had been acoustically calibrated in the context of the GADA system. The apparatus was voltage-calibrated at the beginning of each experimental session and the calibrations were re-checked half way through the session. Signal and noise levels were recorded in terms of the attenuator settings and when the data were transformed into analysis format the levels were converted into sound pressure levels (SPL). The system had been previously checked and was known to be linear throughout the range of voltage levels used in these experiments.

Analysis of the Data

For each block there were two stimulus values and two percent-correct scores [p(c)]. The p(c) values were converted into values of the detection index, d', using the table prepared by Blosser (1965). The data in this format were punched on paper tape and were then entered into the Digital Equipment Corporation

PDP8/S computer in the Signal Detection Laboratory. A regression program for fitting a linear function to the data points by a least squares fit procedure was used in the analysis. The output of the regression program included the mean stimulus value, the mean d', the standard deviation of the stimuli and of d', the slope of the line best fitting the data, the correlation between the stimuli and values of d', the *x* intercept of the line at d' = 1.0, and the slope of the regression line expressed in degrees.

A standard procedure used in analyzing data from a psychophysical experiment is to determine a psychophysical function which best describes that data. In TSD the coordinates have often been d' vs. $(2E/No)^{1/2}$. These were not used. Egan, Lindney, and McFadden (1965) proposed $d' = m(E/No)^k$ as a function that would better fit a straight line to human psychophysical data. In the Signal Detection Laboratory the regression program, therefore, fits functions in a coordinate system of 10 logd' vs. the value of the stimuli in decibels. The equation is solved for *K*, the slope of the best fitting regression line.

The two-level method was developed by Lucas and Watson (1968) in order to reduce the variance found in the older method of collecting many blocks of data and fitting a single function to all of the data. The variance in the standard method was believed to be due to earphone placement, fatigue toward the end of a session, and day-to-day changes in the state of the subject. With the two-level method an attempt was made to reduce some of these effects by fitting a line to the data from each individual block of 100 trials (a five-minute run). From experience it had been found that the final slope of 1.0 which described the psychometric function, included near-chance to near-perfect detection over a range of 12-14dB. However, other evidence suggests that the slope of the function is steeper than this; certainly the smaller ranges of values from the method of adjustment contradicts the finding of a slope of 1.0. If the slope of the psychometric function is determined by a single fit to all of the data from an experiment, then the more variance in the set of data, the less steep the slope will be. With the two-level method it was thought that the average slope would prove to be steeper, because of the reduced effects of block-to-block and day-to-day variability.

The problem with the two-level data was that the variance in the slope and the intercept was naturally quite large, because of the small number of trials in a single block. In order to reduce the variance a method for determinigg extreme values was used (Dixon and Massey, pp. 275-278, 1957). The statistical treatment for elimination of extreme values was applied only to the slopes for they showed greater variance than did the intercepts.

Results

Experiment 1.

The first experiment was run in order to determine the CR's at each of the frequencies, 125, 1000, and 4000Hz, for the four listeners. The data were treated in the coordinate system of 10 logd' vs. S/No. Statistics calculated for each block of 100 trials were the slope of the psychometric function and the x intercept for d' = 1.0, as shown in Table 6. These intercepts are within 2dB of the estimates of the CR by Hawkins and Stevens (1950). Listed also on the table are the within-subject standard deviations (in parentheses). The table supports three accepted facts about the CR. The first is that with a moderate level of masking noise, a subject will have very consistent performance for a constant value of S/No. The second is that the CR is fairly constant across normal listeners. Finally, the CR increases as expected with the frequency of the signal.

Experiment 2.

The second experiment was run to determine the signal level required for d' = 1.0 in the absence of external masking noise at the same three frequencies. As shown in Table 7, the within-subject standard deviations are again small. The between-subject standard deviations are larger, due to the difference in the lower limit of sensitivity between subjects. Subject sensitivity ranges both above and below normal audiometric thresholds at all frequencies (Davis and Kranz, 1964). As a group, the signal levels required for d' = 1.0 are slightly lower than audiometric zero and are also lower than the levels found by Watson, Franks, and Hood (1967) in their study of detection in the absence of external noise. Their mean levels for twelve subjects were 46.5dB SPL at 125Hz, 9.0dB SPL at 1000Hz, and 14.5dB SPL at 4000Hz. The differences are not significant, and are therefore assumed to reflect only sampling variability.

Table 6. Critical Ratios from the First Experiment.

Subject	Frequency 125Hz	1000Hz	4000Hz
1	16.7dB*	18.0dB	24.8dB
	(0.8)	(2.4)	(1.2)
2	18.3	21.6	24.5
	(1.4)	(0.9)	(0.5)
3	14.9	19.9	24.5
	(2.0)	(0.9)	(1.4)
4	18.0	21.3	23.1
	(1.2)	(1.0)	(0.8)
$\overline{X}$	16.9	20.2	24.2
S.D.	1.6	1.6	0.8
$S_{\overline{X}}$	0.8	0.8	0.4
Hawkins & Stevens (1950)	17.0	19.0	25.0

*Each value is the ratio of signal to noise spectrum level required to obtain d'=1.0, in the presence of masking noise with spectrum levàls of 50dB (125 and 1000Hz) or 40dB (4000Hz) SPL.

Table 7. Signal Level for d' = 1.0 Detection for Second Experiment

	Frequency		
Subject	125Hz	1000Hz	4000Hz
1	48.2dB*	0.2dB	2.7dB
	(1.7)	(1.6)	(2.5)
2	47.9	7.2	17.1
	(1.8)	(0.8)	(1.8)
3	39.8	2.9	10.8
	(2.4)	(0.7)	(2.7)
4	43.3	0.7	23.0
	(1.8)	(1.9)	(2.2)
$\overline{X}$	44.7	2.8	13.4
S.D.	4.0	3.2	8.7
$S_{\overline{X}}$	2.0	1.6	4.4

*Values are given in decibels relative to 0.0002 microbar.

Estimation of Internal Noise Levels from Critical Ratios.

A common purpose of the first and second experiments was to provide an internal noise estimate to be compared to that obtained in the third experiment. The hypothesis was that an internal noise, at a given frequency, would be one CR below the level of signal required for detection at $d' = 1.0$ in the absence of external noise. The formula for calculation was thus

$$10 \cdot \log (No_i)_f = S_f - CR_f \qquad \text{(Eq. 1.)}$$

where No_{if} is the estimated effective masking level of the internal noise, S_f is the signal level in decibels required for $d' = 1.0$ in the quiet for frequency f, and CR_f is the CR for frequency f, in decibels. These estimates are shown in Table 8.

Experiment 3.

The third experiment was run to obtain a second type of estimate of the internal noise level. Four levels of masking noise were presented, $No_e = -\infty$, No_e at 3dB greater than the internal noise (No_i) estimated from Experiments 1 and 2, No_e at the estimate, and No_e at 3dB less than the No_i estimate. The data were again analyzed in the coordinate system, $10 \cdot \log d'$ vs. S/No_e.

Slopes of the Psychometric Functions. The slopes of the psychometric functions from Experiment 3, along with the slopes from the first and second experiments are presented in Table 9. Since the differences between the slopes from the first and second experiments are not significant the interpretation of detection in the "quiet" as a masking condition, with internal noise as the masker, is once again supported.

Table 8. Estimated Internal Noise Levels By Equation 1.

	Frequency		
Subject	125Hz	1000Hz	4000Hz
1	31.5dB*	-17.8dB	-22.1dB
2	29.6	-14.3	-7.4
3	24.9	-17.0	-13.7
4	25.2	-20.6	0.0
$\overline{X}$	27.8	-19.4	-10.8

*Each value is estimated by calculating the difference between the level of signal required to yield d' = 1.0 in the quiet, obtained in Experiment 2, and the CR as measured in Experiment 1. For example, for Subject 1, from Tables 6 and 7,

$$48.2 - 16.7 = 31.5.$$

Table 9. Slope of Psychometric Functions from Experiments 1, 2, and 3.

Experiment	Subjects	125Hz	1000Hz	4000Hz
		Frequency		
	1	53.5*	53.0*	54.7*
1	2	49.4	53.5	58.5
	3	56.2	51.1	50.7
	4	50.5	46.7	55.7
	$\overline{X}$	52.4	51.1	54.9
	S.D.	3.1	3.1	3.2
	Tangent	1.30	1.24	1.42

Experiment	Subject	125Hz	1000Hz	4000Hz
		Frequency		
	1	55.9*	55.1*	55.7*
2	2	49.4	56.1	53.9
	3	41.6	54.1	48.4
	4	60.6	54.1	44.1
	$\overline{X}$	51.9	54.8	50.5
	S.D	8.2	1.0	5.3
	Tangent	1.28	1.42	1.21

Table 9. (Cont'd.)

Experiment	Subject	Frequency 125Hz	1000Hz	4000Hz
	1	15.4°*	23.1°	15.6°
	2	16.0	23.9	22.8
3 (S/No_e)	3	6.9	18.7	15.1
	4	22.3	20.7	16.0
	$\overline{X}$	15.2	21.5	17.4
	S.D.	6.3	2.3	3.6
	Tangent	0.27	0.39	0.31

Experiment	Subject	Frequency 125Hz	1000Hz	4000Hz
	1	58.5°*	61.8°	53.1°
	2	58.1	64.7	68.8
3 (S/No_t)	3	49.9	68.4	66.6
	4	55.9	61.3	62.9
	$\overline{X}$	55.0	64.0	62.8
	S.D.	4.9	3.3	6.9
	Tangent	1.43	2.05	1.95

*The slopes given in the third section of the Table are for psychometric functions, fitted in the coordinate system, $10 \cdot \log d'$ vs. $10 \cdot \log S/No_e$ for the low levels of No_e used in Experiment 3. The fourth section shows estimates of the slope for the same psychophysical data, but the psychometric functions were re-fitted in the coordinate system $10 \cdot \log d'$ vs. $10 \cdot \log S/No_t$, where $No_t = No_e + No_i$, and No_i is the estimated internal noise level as calculated by Equation 1 and shown in Table 8.

It is obvious that the slopes obtained in Experiment 3 are considerably less steep than the slopes from the first and second experiments. If the signal is only a few decibels above the level required for $d' = 1.0$ in the quiet, and <u>if there is some internal noise</u>, then the amount of change in the overall signal-to-noise ration (S/No_t) will be less than the change in the external noise would imply. Consequently the lower slopes, as observed, are consistent with the internal-noise hypothesis.

The last section of Table 9 gives another set of slopes for the third experiment. In this section a regression equation was fitted in the coordinate system, 10 logd' vs. S/No_t, where

$$No_t = 10 \cdot \log[10^{(No_e/10)} + 10^{(No_i/10)}],$$

and the values of No_i are those given in Table 8. Note that these slopes are quite close to those for Experiments 1 and 2; however, they are slightly larger, on the average (p 0.01), than those obtained in the earlier experiments. The small increase in the slope is an indication that not enough internal noise was predicted by the CR hypothesis. It also follows that had a more accurate value of No_i been assumed, then the slopes for the psychometric functions of the third experiment, plotted on S/No_t, would be the same as for the other two experiments.

Table 9 shows the slopes of the psychometric functions for all three experiments, expressed in degrees rather than in the more conventional value of the tangent. Watson, Lucas, and Franks (1968) found that avergging of tangents leads to invalid estimates of the mean slope, because the function tan(x) is discontinuous over the range of interest. The mean slope for four subjects and the related standard deviations are given for each frequency in degrees, and the tangent of the mean is also presented in this table. As expected, the tangents in Experiments 1 and 2 are always greater than 1.0, supporting the earlier prediction that variability would be reduced, and steeper psychometric functions obtained, by fitting data within, rather than between, blocks of trials.

Critical Ratio with Low-level External Noise. Table 10 contains the CR's for the third experiment, which were obtained from psychometric functions with S/No_t as the abscissa (with No_t estimated as above). These CR's are not significantly different from those found in the first experiment, thus supporting the hypothesis that the effective internal noise level may be estimated from the CR. However, if it is kept in mind that the slope may change from 40° to 70° with little change in the intercept value, then it is clear that the CR is not a fine enough measure to give much accuracy in obtaining an estimate of No_i.

Estimation of Internal Noise from Low-level Masking. Another way of estimating the level of internal noise is based in the difference between the signal level required for $d' = 1.0$ in the absence of external noise (S_{dB}) and the amount of noise (No_{edB}) required as a masker to obtain $d' = 1.0$ with a signal a few decibels greater than the one used in the absence of noise.

If masking at low levels of external noise is assumed to increase one decibel for each decibel increase in No_t, then the

Table 10. Critical Ratios from the Third Experiment on the Coordinate System $10\cdot\log d'$ vs. $10\cdot\log(S/No_t)$.

	Frequency		
Subject	125Hz	1000Hz	4000Hz
1	15.5dB	19.1dB	29.6dB
	(1.2)	(1.3)	(4.6)
2	19.3	20.8	25.9
	(0.5)	(1.6)	(1.2)
3	16.1	19.5	26.0
	(1.3)	(1.5)	(1.0)
4	19.4	22.3	22.5
	(1.2)	(0.9)	(1.5)
$\overline{X}$	17.6	20.4	26.0
S.D.	2.1	1.4	2.9
$S_{\overline{X}}$	1.55	0.70	1.45

level of No_i may be estimated from the external noise (No_e) required to achieve d' = 1.0, when the signal (S_{dB}) is raised by a few decibels ($\Delta S = C_{dB}$) from that signal level required for the same performance in the quiet. That is, the increase in No_t is assumed to be the same as the increase in signal level, C_{dB}, for constant performance. Thus,

$$10 \cdot \log (No_e + No_i) = 10 \cdot \mathrm{Log} No_i + C_{dB},$$

or equivalently,

$$10 \cdot \log \left(\frac{No_e + No_i}{No_i} \right) = C_{dB}.$$

Dividng both sides by 10 and distributing the denominator of the noise ratio,

$$\log \left(\frac{No_e}{No_i} + 1 \right) = C_{dB}/10.$$

If the expression is then raised to a power of 10,

$$\left(\frac{No_e}{No_i} + 1 \right) = 10^{C/10},$$

and in solving for the internal noise,

$$No_i = \frac{No_e}{10^{C/10} - 1},$$

or in decibels

$$10 \log(No_i) = 10 \log(No_e) - 10 \log[10^{(C/10)} - 1]. \qquad \text{(Eq. 2.)}$$

The values for S_{dB}, $(S + G)_{dB}$, and C_{dB} are in Table 11. The values for No_i calculated from Eq. 2 and from Eq. 1 (see also Table 8) are shown in Table 12. The third estimate of No_i shown in Table 12 will be discussed in a later section.

Table 11. Values of S, S + C, and C

for Estimating No_i Given No_e Required for d' = 1.0.

Signal Level Required for d' = 1.0_{II}. (S)

Subject	Frequency 125Hz	1000Hz	4000Hz
1	48.2dB	0.2dB	2.7dB
2	47.9	7.2	17.1
3	39.8	2.9	10.8
4	43.3	0.7	23.0

Signal Level Used in Experiment 3. (S + C)

Subject	Frequency 125Hz	1000Hz	4000Hz
1	49.7dB	1.8dB	5.0dB
2	50.5	7.8	19.8
3	43.8	3.2	12.4
4	46.5	2.5	24.2

Increment in Signal Level Introduced in Experiment 3. (C)

Subject	Frequency 125Hz	1000Hz	4000Hz
1	1.5dB	1.6dB	2.3dB
2	2.6	0.6	2.7
3	4.0	0.3	1.6
4	3.2	1.8	1.2

Table 12. Internal Noises As Estimated by Equations 1, 2, and 3.

Equation	Subject	125Hz	1000Hz	4000Hz
			Frequency	
1*	1	31.5dB	-17,8dB	-22.1dB
	2	29.6	-14.3	-7.4
	3	24.9	-17.0	-13.7
	4	25.2	-20.5	0.0
	$\overline{X}$	27.8	-17.4	-10.8
	S.D.	3.27	2.55	9.39

Equation	Subject	125Hz	1000Hz	4000Hz
			Frequency	
2*	1	34.1dB	-19.5dB	-28.9dB
	2	26.6	-11.4	-12.5
	3	22.1	-13.5	-20.0
	4	20.6	-24.1	1.2
	$\overline{X}$	25.8	-17.1	-12.6
	S.D.	6.06	5.78	14.29

Table 12. (Cont'd.)

Equation	Subject	125Hz	1000Hz	4000Hz
			Frequency	
	1	32.7dB	-17.8	-22.6
	2	32.1	-17.8	-8.9
3*	3	30.9	-18.5	-20.0
	4	27.2	-22.5	0.2
	$\overline{X}$	30.3	-18.4	-12.8
	S.D.	2.29	3.17	10.52

*See the text for details.

An analysis of variance showed no significant difference between the two estimates of No_i from Eq. 1 and Eq. 2. The methods of estimation were independent, and thus provided a separate way of evaluating the CR hypothesis. Of course, the lack of a significant difference does not in itself confirm the CR hypothesis.

Relation Between Slope of Psychometric Function and Internal Noise. If there is an internal noise, then the change in the overall noise level (No_t) at low levels of external noise (No_e) will be less than the levels of No_e suggest. If there were no internal noise, then the change in No_t would be entirely equivalent to the change in No_e. The slopes of the psychometric functions for low-level masking would be the same as the slopes for high-level masking. This was shown not to be true in Table 9. It was also shown earlier that if a value of internal noise was assumed from the CR hypothesis (Eq. 1) and the psychometric function then was plotted with S/No_t rather than S/No_e on the abscissa, that the slopes for low- and high-level masking were almost equal. To further illustrate this point, hypothetical psychometric functions were contructed for several assumed values of No_i. The procedure for constructing these functions is as follows.

First the signal-to-noise ratios required for several values of d' were calculated from the linear equation introduced earlier (Egan, Lindner, and McFadden, 1965),

$$10 \cdot \log d' = K[10 \cdot \log(S/No)] + B, \qquad \text{(Eq. 3.)}$$

using the values of K obtained in Experiment 2. These values of S/No are shown in Table 13, column 1, for the values of d' in column 2. The remaining columns in Table 13 show the values of d' to be expected for each of the signal-to-noise ratios in column 1, _if_ some internal noise is presented in the system. For example, consider the third row of the table, for $S/No_e = 27.281$. In column 5 an internal noise (No_i) that is 5dB less than that predicted by Eq. 1, has been assumed. If the abscissa is considered to represent a constant signal level, so that S/No varies only with No, then for each value of No_e we may calculate a corresponding value of No_t, by

$$No_t = No_e + No_i.$$

Thus for each value of S/No_e we have a corresponding value of S/No_t, for which a new predicted performance level (d') may be calculated from Eq. 3. In our example of row 3 if there is no internal noise and $No_e = 27.281$dB we would expect d' to be 2.0, but if No_i is real and equal to 24.6dB (5dB less than that predicted by Eq. 1), No_t will have only increased to 0.629dB over that required for d' = 1.0. The performance expected for this S/No_t is d' = 1.408 (col. 5), considerably less than would be expected with no internal noise (col. 2). These same calculations were also made for assumed internal noises of +5 (col 3), 0 (col. 4), and -10 (col. 6) dB re the internal noise levels calculated with Eq. 1. The resulting psychometric functions are shown for one of the listeners (S2) in Figures 4 and 5. The same functions are plotted in terms of the transformation of d' to percent correct (2ATFC) (Blosser, 1965) in Figures 6 and 7.

Table 13. Values of d' as a Function of S/No_e Given an Assumed No_i. (S-2)*

1	2	3	4	5	6
			d'		
S/No_e	$No_i = -\infty$	$No_i = 34.6$	$No_i = 29.6$	$No_i = 24.6$	$No_i = 10.0$
38.3dB	38.5	1.15	1.47	2.50	22.9
33.3	10.0	1.13	1.43	2.31	8.42
28.3	2.6	1.08	1.23	1.56	2.50
27.8	2.3	1.07	1.21	1.49	2.23
27.3	2.0	1.06	1.18	1.41	1.95
26.7	1.7	1.05	1.14	1.31	1.67
25.9	1.4	1.03	1.09	1.19	1.39
25.1	1.1	1.01	1.03	1.05	1.09
24.7	1.0	1.00	1.00	1.00	1.00
23.9	0.8	0.97	0.93	0.88	0.80
22.1	0.5	0.90	0.78	0.64	0.51
18.7	0.2	0.71	0.48	0.32	0.20

* These are the values of d' as a function of S/No_e used to fit the psychometric functions shown in Tables 4 and 6 basedd on data from S-2 at 125Hz.

Table 13. (Cont'd.)

1	2	3	4	5	6
			d'		
S/No_e	No_i=--	No_i=-9.3	No_i=-14.3	No_i=-19.3	No_i=-30.0
34.4dB	10.0#	1.01	1.29	1.90	6.53
32.0	4.37	1.07	1.22	1.61	3.54
30.7	2.6	1.04	1.13	1.33	2.45
30.3	2.3	1.04	1.12	1.29	2.21
29.9	2.0	1.03	1.10	1.24	1.96
29.5	1.7	1.03	1.09	1.19	1.71
28.9	1.4	1.02	1.05	1.12	1.44
28.2	1.1	1.00	1.01	1.03	1.27
27.9	1.0	1.00	1.00	1.00	1.00
27.3	0.8	0.98	0.96	0.92	0.87
25.9	0.5	0.95	0.87	0.76	0.56
23.2	0.2	0.85	0.67	0.48	0.23

#These are the values of d' as a function of S/No_e used to fit the psychometric functions shown in Tables 5 and 7 based on data from S-2 at 1000Hz.

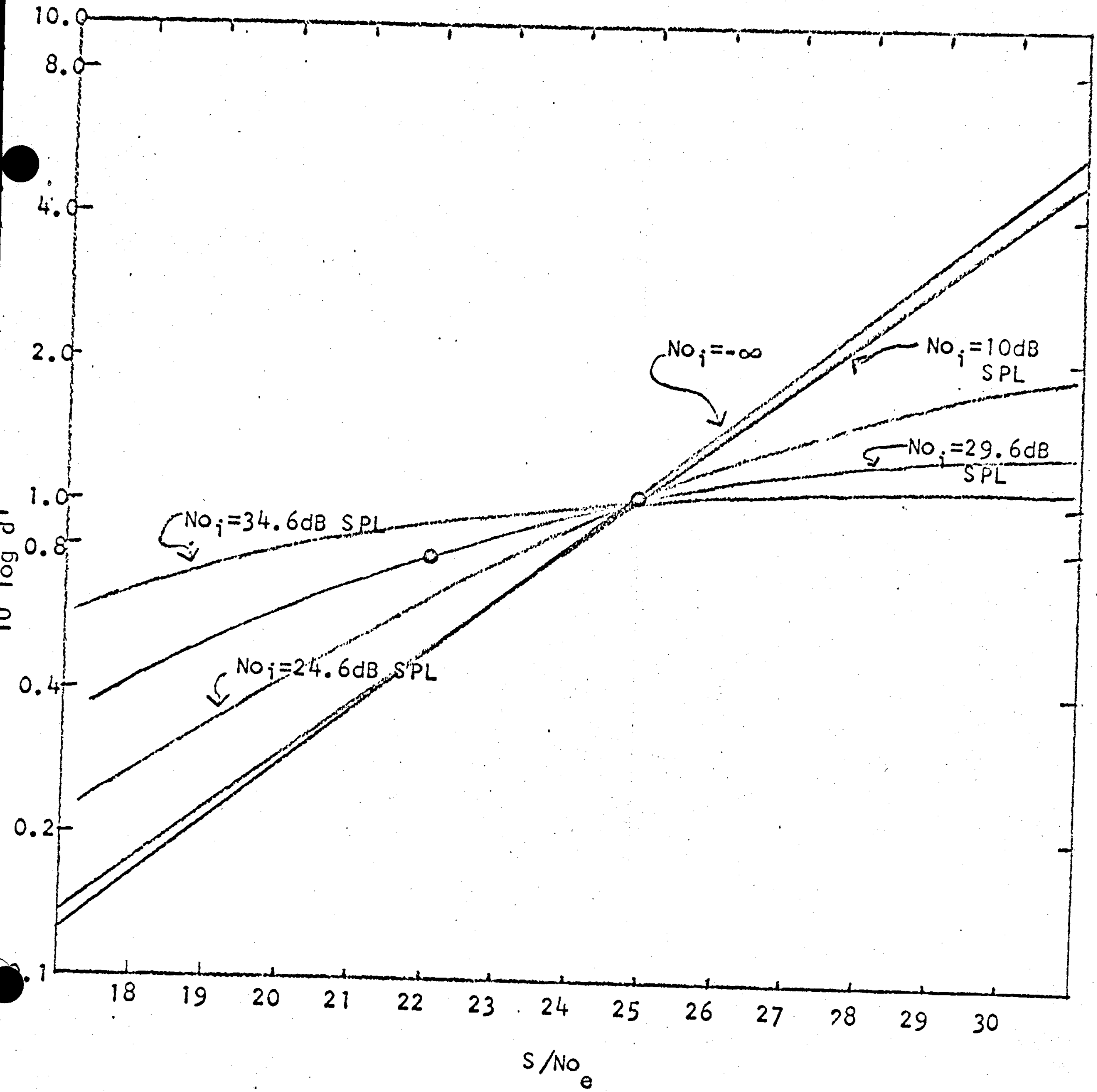

Fig. 4. Psychometric functions as related to level of No_i for S-2 at 125Hz: The solid circles show data points. See text for fitting procedure.

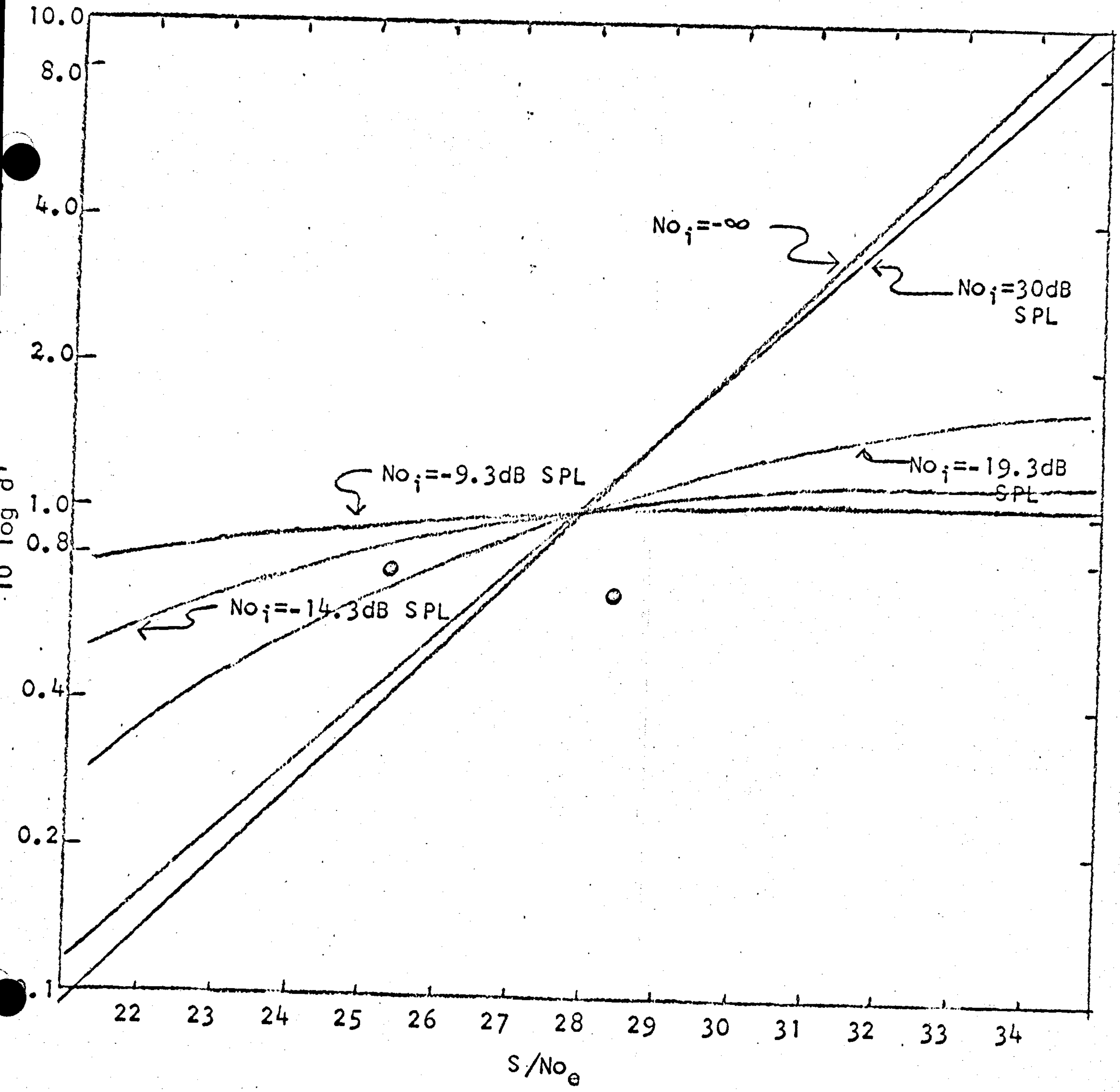

Fig. 5. Psychometric functions as related to No_i for S-2 at 1000Hz. Solid circles show data points. See text for fitting procedure.

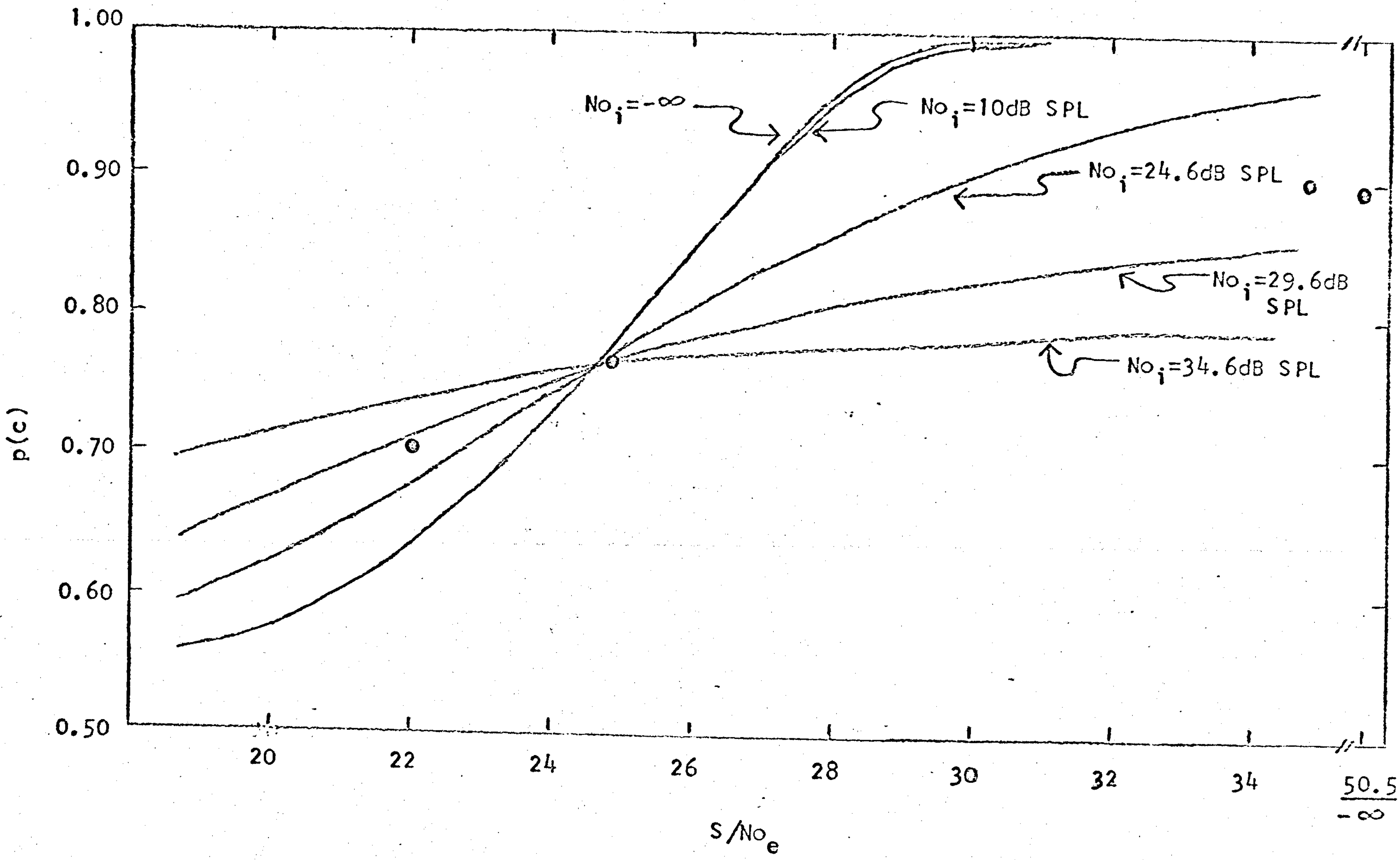

Fig. 6. Psychometric functions as related to No_i for S-2 at 125Hz. Solid circles show data points. See text for fitting procedure.

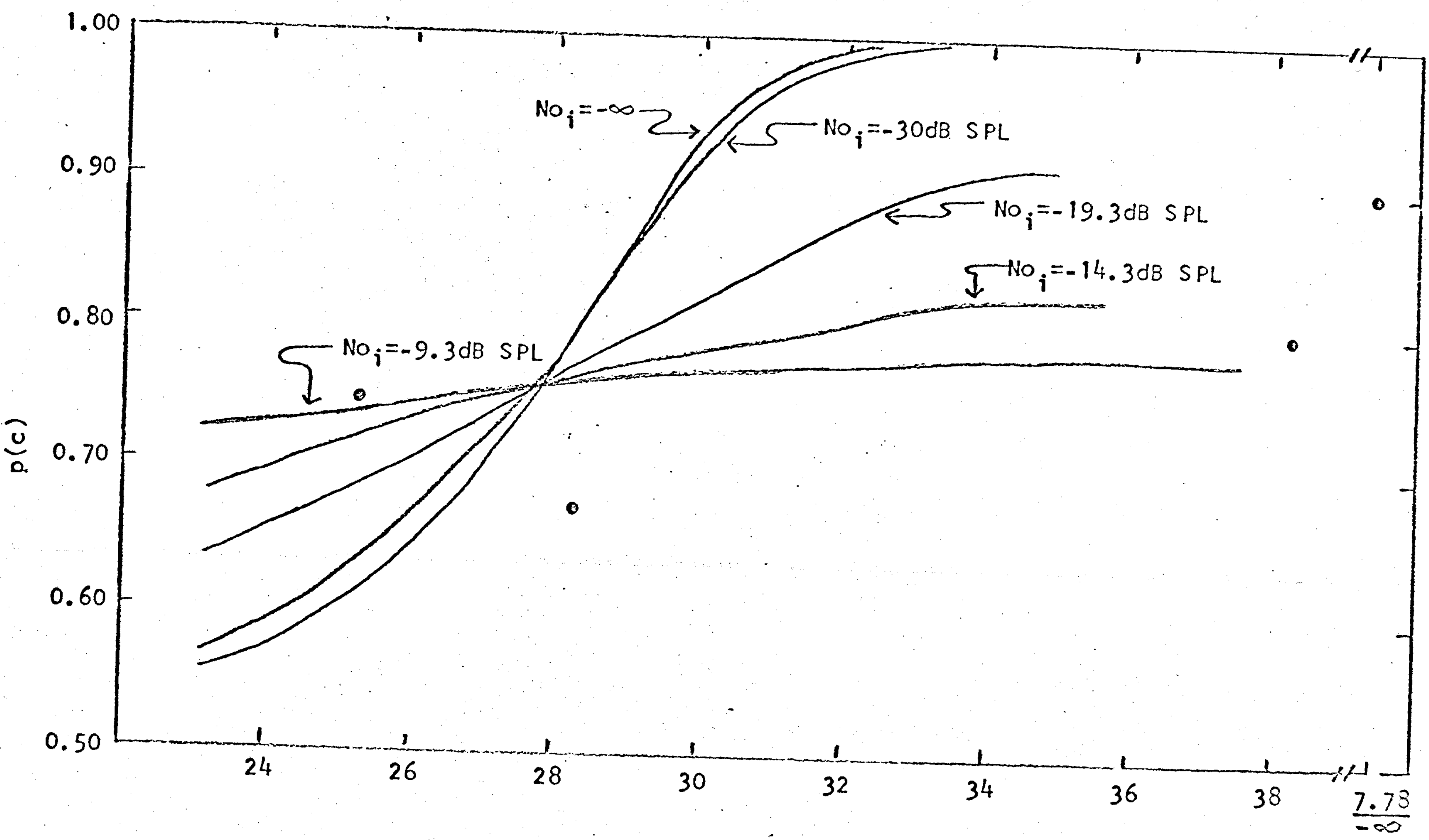

Fig. 7. Psychometric functions as related to No$_i$ for S-2 at 1000Hz. Solid circles are data points. See text for fitting procedure.

The data points for S-2 are also plotted on Figures 4 through 7. They fall fairly close to the curve for No_i = 24.6dB SPL at 125Hz. That curve is the function for No_i resulting from Eq. 1. At 1000Hz the data are so variable that it is difficult to tell on which function they fall.

By taking the points from Table 13 that fall between d' = 0.35 and d' = 1.19 [p(c) from 0.60 to 0.80], the most linear part of the function, the slope of each function can be computed, using Eq. 3. Figures 8 and 9 are nomograms, showing the slope of the psychometric functions as a function of the amount of assumed internal noise.

The slopes for the third experiment from Table 9 can now be evaluated on these nomographs. For S-2, at 125Hz, Table 9 shows a slope of 16° (tan 16° = 0.28), and the corresponding value of No_i from Figure 8 is +2.5dB relative to the No_i from Eq. 1. Therefore the <u>slope</u> estimate of No_i is 29.6dB (from Table 8) plus 2.5dB, or 32.1dB. Figure 9 shows a similar nomograph for S-2 at 1000Hz. This procedure was repeated for each S, at each frequency and the resulting values of No_{idB} are shown in Table 12. An analysis of variance showed no significant difference between the three estimates of No_i. The fact that a slope was computed for a somewhat non-linear function in the last procedure reduces its accuracy, but the departures from linearity were small.

Figure 10 shows the relation between signal level required for d' = 1.0 in the absence of external noise, the No_i estimated by the CR hypothesis (Eq. 1), and the noise measured by Shaw and

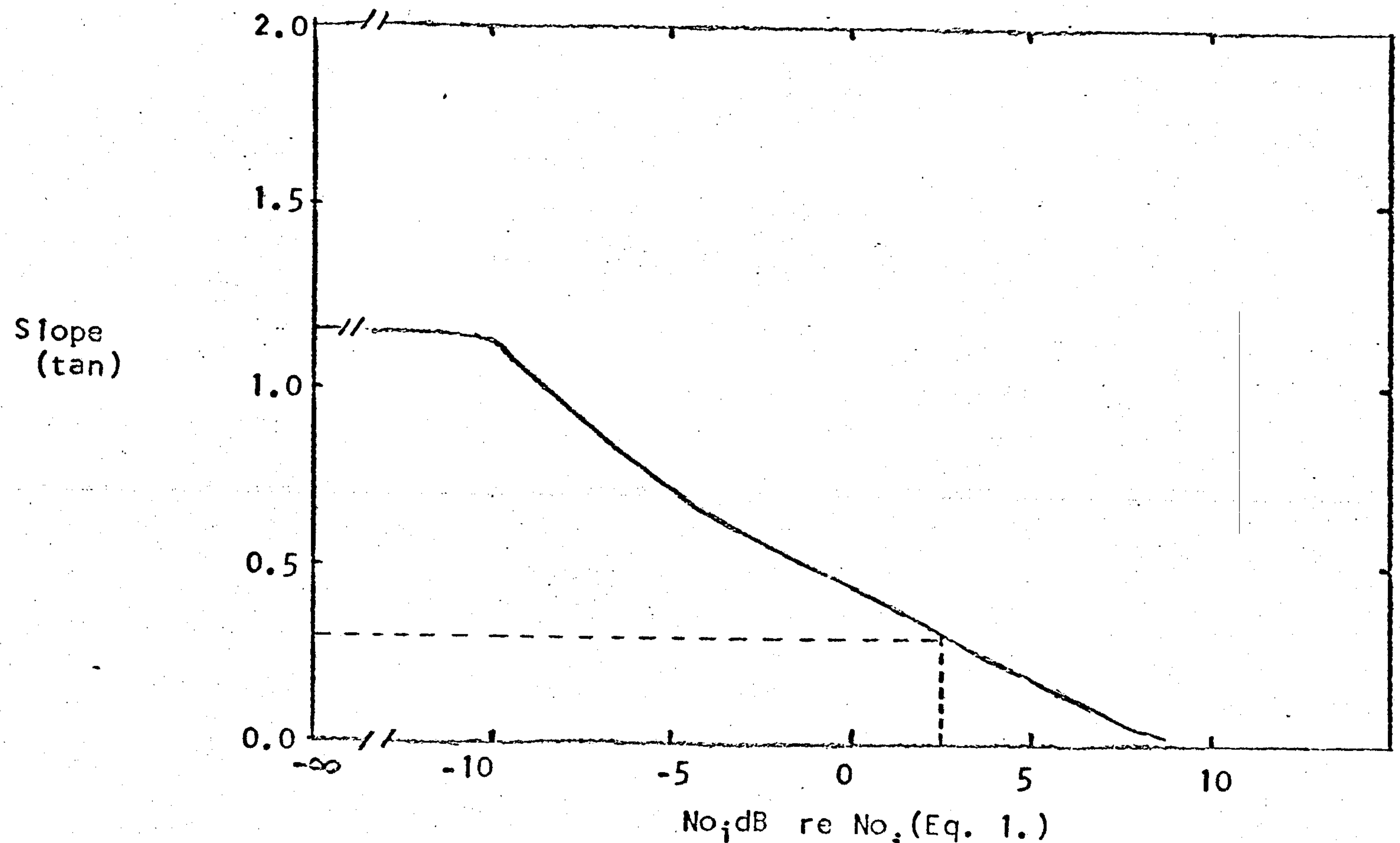

Fig. 8. Slope of psychometric functions for S-2 at 125Hz as function of No_i. See text for explanation.

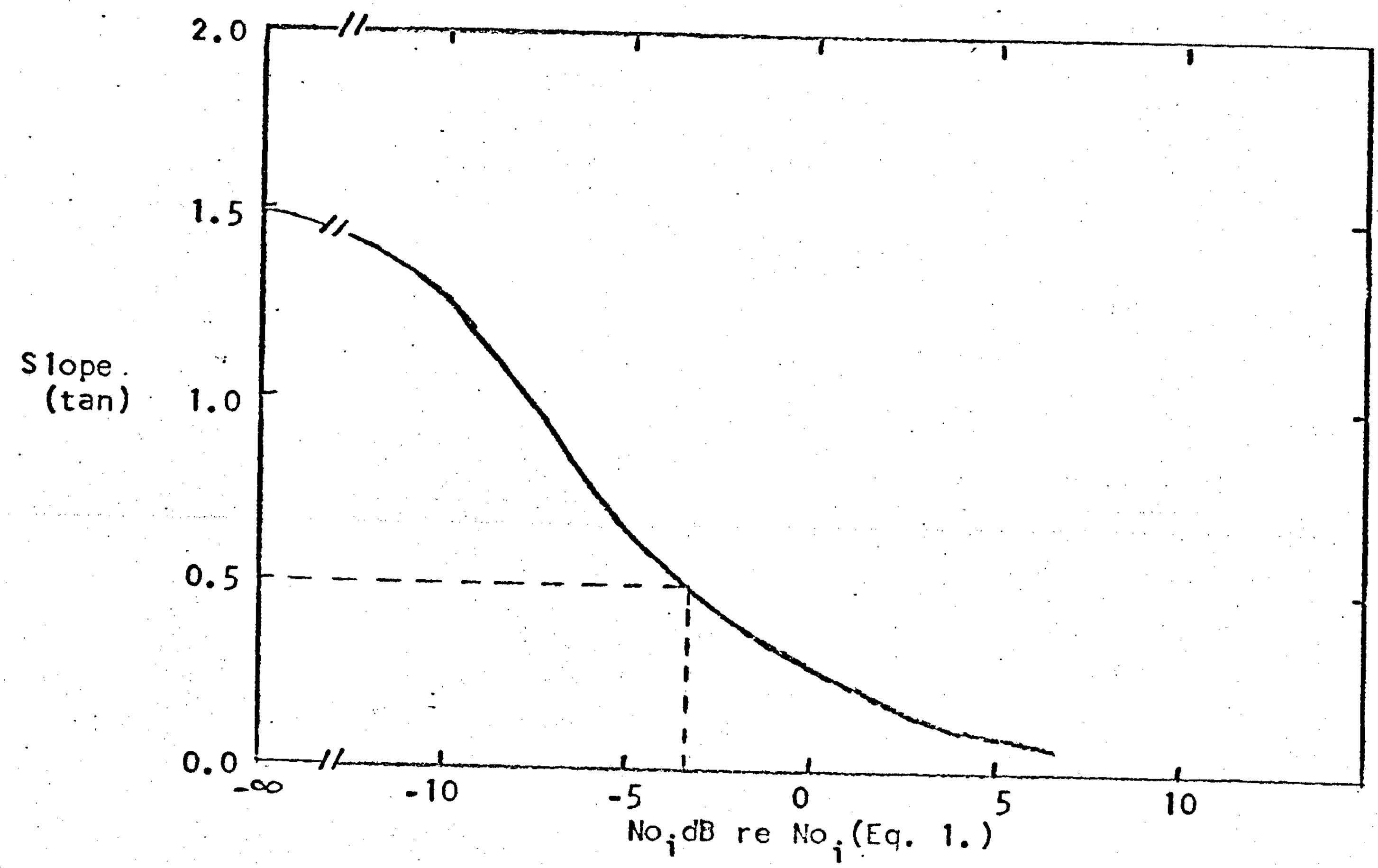

Fig. 9. Slope of psychometric functions for S-2 at 1000Hz as function of No_i. See text for explanation.

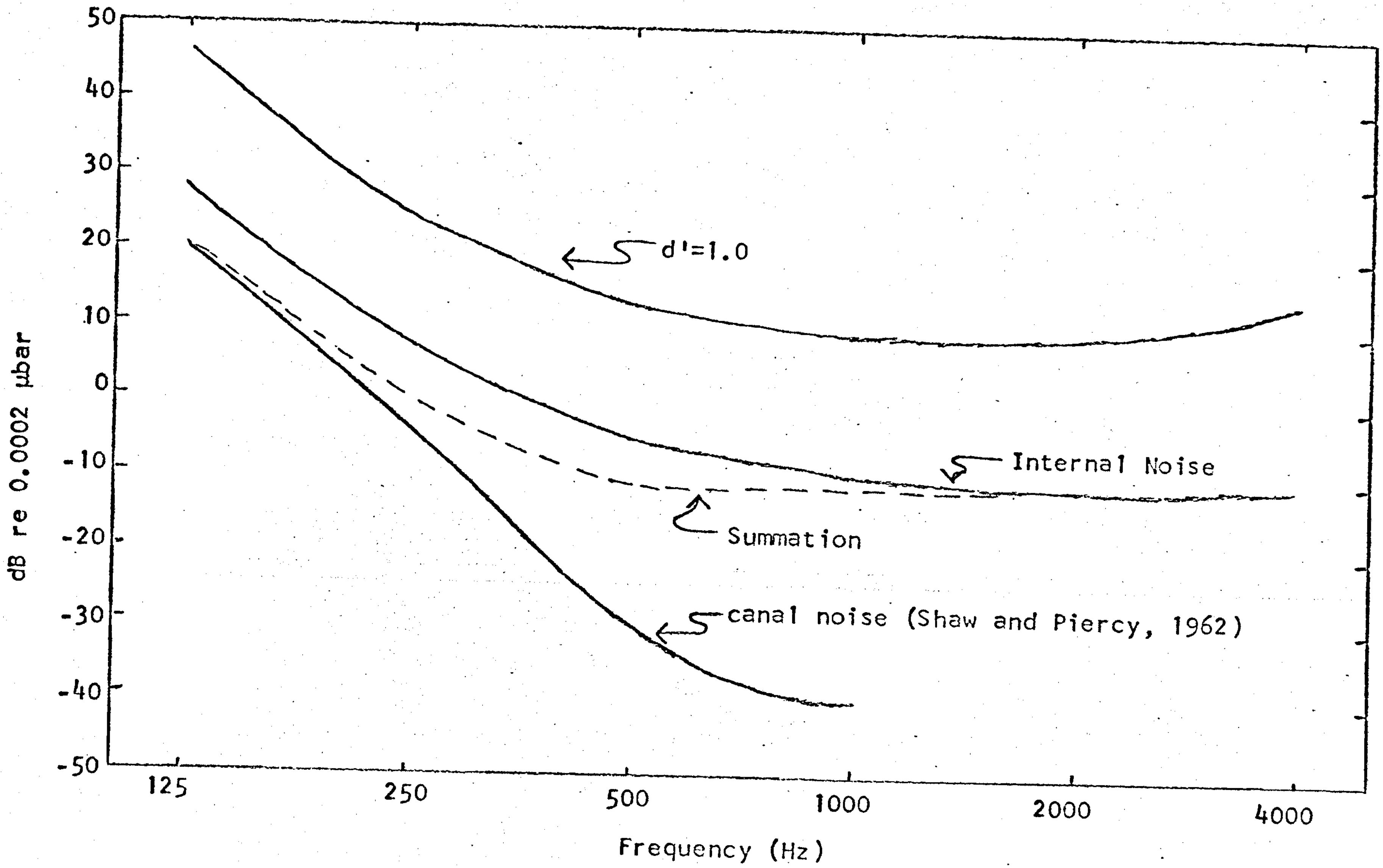

Fig. 10. Comparison of the level required for d'=1.0 in the quiet with the internal noise as estimated by Eq. 1, with the ear canal noise measured by Shaw and Piercy (1962), and with the summation of the two noises as a function of frequency.

Piercy (1962) under the MX41/AR earphone cushion as a function of frequency. One of the assumptions of this paper was that there may be two separate noise distributions serving as internal maskers; one due to physiologic noise in the ear canal, the other due to a constant-level neural noise. The data used for establishing the signal level required for d' = 1.0 in the quiet are from the 12 subjects of Watson, Franks, and Hood (1967) who were tested in the absence of external masking noise at 125, 250, 500, 1000, 2000, and 4000Hz. The CR's usdd to estimate No_i are from Hawkins and Stevens (1950).

From Figure 10 it can be seen that the internal noise reaches an assymptotic level at about -11dB SPL, and if the only other source of noise was that in the ear canal at low frequencies as measured by Shaw and Piercy (1962), then the addition of these two noises should be the behaviorally-estimated internal noise curve. This simple additive rule does not account for the level of the internal noise estimated by the CR hypothesis below 1000Hz. As shown by the dashed curve of Figure 10 (representing the sum of a frequency-independent noise at -11dB, and the ear-canal noise), there seems to be another noise source which has not yet been considered at low frequencies which would increase the total No_i by 9dB at 125Hz, 9dB at 250Hz, and 6dB at 500Hz above the combined level of neural noise and canal noise.

Discussion and Conclusions

The central hypothesis of this thesis was that the CR is constant and independent of the amount of external noise and that consequently the so-called "absolute" threshold is really a masked threshold with internal noise, a CR below the signal at threshold, serving as the masker. The experiments discussed here are a partial replication of a study by Watson, Franks, and Hood (1967) in which the CR hypothesis was used to estimate the effective spectrum level of the internal noise.

An additional hypothesis was that the slope of the psychometric function at low levels of the masking noise could be predicted from the CR-based estimates of internal noise. Another hypothesis was that there were two sources of internal noise; one due to the physiologic noise in the ear canal decreasing in level with frequency, the other being a constant level neural noise with the two combining to yield an effective internal noise level one ~~CN~~ CR below the threshold for the signal in the quiet.

Three methods of estimating the level of the internal noise were discussdd and attempted. The first method was to subtract the CR from the signal level required for d' = 1.0 in the quiet. The second was the estimation of an internal noise level, based on the amount of low-level external masker required for d' = 1.0, when the signal level was increased by a few decibels from that required for d' = 1.0 in the absence of external masking. The third method involved predicting the slope of the psychometric function in the coordinate system, 10•logd' vs. S/No_e, for low valu values of No_e and then finding the internal noise value that would yield this slope.

There was no significant difference in the amount of internal noise estimated by the three methods. Therefore, no statements may be made as to which method gives a "true estimate." While the critical-ratio hypothesis is not entirely validated by these experiments, the consistency of the three estimates of No_i gives it strong support.

It became clear that the two-noise-distribution hypothesis (neural plus canal noise) cannot entirely account for the effective level of No_i. A third, low-frequency, noise source must be present, though at this time its source is not clear.

The experiments show that the auditory system does behave as though there is an internal noise setting the lower limit of sensitivity. Consequently the concept of the CR as a description of the mode of signal processing by the auditory system may be applied to low- as well as high-level signals.

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